DESIGN AND DEVELOPMENT OF AN APPARATUS FOR DEMONSTRATING THE NATURAL FREQUENCY OF A VIBRATING SYSTEM.

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SUBMITTED TO:

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IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF BACHELOR OF ENGINEERING (B.ENG) DEGREE IN MECHANICAL ENGINEERING

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DECLARATION

We declare that this project titled **"Design and Development of an Apparatus for Demonstrating the Natural Frequency of a Vibrating system"** is an original work carried out by the underlisted students in partial fulfillment of the requirements for the award of Bachelor of Engineering Degree in the Department of Mechanical Engineering, University of Calabar, Calabar. All extracts from different sources of information used are duly acknowledged.

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CERTIFICATION

This is to certify that the research work titled: "**Design and Development of an Apparatus for Demonstrating the Natural Frequency of a Vibrating system"** was carried out by Ogbonna Nkechukwu Chukwuemeka with matriculation number: 18/186145016, Iheanacho Justin Chinweze with matriculation number: 18/184145035, Okeke Michael Chukwubuikem with matriculation number: 18/186145019, Agba Bekwuhapu Sylvester with matriculation number: 18/185145002, Alali-Michael Favour Kingsley with matriculation number: 18/184145004, Adah Favour Tabi, with matriculation number: 16/186145001, Ujaga Joemary Anorishor with matriculation number: 18/184145023 all of the department of Mechanical Engineering was duly supervised by us and found worthy of acceptance in partial fulfillment of the requirements for the award of B.ENG. degree in Mechanical Engineering, Faculty of Engineering and Technology, University of Calabar.

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DEDICATION

This project is dedicated to the Almighty God, the giver of life, knowledge, understanding and wisdom.

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ABSTRACT

The project involves the design and development of an apparatus for demonstrating the natural frequency of a vibrating body. It is an inherent property of the system, determined by its physical characteristics such as mass, stiffness, and geometry. The natural frequency of a body is an important parameter in designing and analyzing mechanical systems so as to ensure the design won't resonate. The apparatus is user friendly and cost-effective, making it suitable for educational and research purposes. The project aims to provide a hands-on learning experience for students and researchers, allowing them to understand the concept of natural frequency in a vibrating body. The apparatus helps to demonstrate various concepts related to vibration such as resonance, damping and forced vibration. It can also be used to understand the effects of various parameters such as length, breath and thickness on the natural frequency of a metal flat bar. The apparatus consist of electric motor with a disc and an unbalanced force attach to it to aid vibration, a metallic frame, a frequency sensor, and a control box. The parts of the apparatus are fabricated using Gas Metal Arc Welding (GMAW) and fastners and designed in such a way that it can be easily disassembled and assembled. A straight forward but efficient method for creating and measuring vibrations in a controlled setting is incorporated into the design. An external force is used to excite the vibrating body, and sensors are used to record its reaction. The system's inherent frequency is ascertained by analyzing the gathered data. The findings show how accurate and dependable the device is at determining the natural frequency, which makes it a useful teaching aid for engineers and researchers. The apparatus showed that there is a relationship between natural frequency and material properties like length, thickness, geometry etc. The experiment emphasizes how crucial experiential learning is to understanding difficult theoretical ideas.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS

Vibration Analysis	(VA)
Electric Submersible Pump	(ESP)
Frequency Response Functions	(FRFs)
Tuned Mass Damper	(TMD)
Dynamic Vibration Absorber	(DVA)
Fiber Metal Laminates	(FML)
Multi-Walled Carbon Nanotubes	(MWCNT)
Layered double hydroxide	(LDH)
Fast Fourier Transform	(FFT)
Shape Memory Alloy	(SMA)
Technique for Order of Preference by Similarity to the Ideal Solution	(TOPSIS)
Root-of-Mean-Square	(RMS)
Multiple-Degree-Of-Freedom	(MDOF)
Frequency Response Function	(FRF)
Laser Doppler vibrometry	(LDV)
Finite Element Analysis	(FEA)
Frequency Domain Decomposition	(FDD)
Stochastic Subspace Identification	(SSI)

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

Natural frequency is defined as the frequency at which a system oscillates when it is not subjected to any external force or damping. It is an inherent property of the system, determined by its physical characteristics such as mass, stiffness, and geometry (Inman, 2014). Mechanical systems and natural bodies vibrate either freely, that is the force is applied only initially, or forced, where the external force is either continuous or periodic. When a body is excited, it tends to vibrate at its natural frequency. This natural frequency can easily be gotten with the help of a concept called resonance. Resonance occurs when a vibrating system enables another body to vibrate at a higher amplitude when it reaches the natural frequency.

A material attached to a vibrating body has its own natural frequency, but it will vibrate at the frequency of the vibrating body. This kind of vibration is called a forced vibration. When the frequency of the vibrating body approaches the material's natural frequency, the material's amplitude increases and is maximum at its natural frequency. Further increment of the frequency of the vibrating body leads to lesser amplitude, causing a normal curve of the resonant amplitude to resonant frequency.

This study is significant because understanding and determining the natural frequency of a vibrating body is crucial. Some engineering problems require us to consider and identify the natural frequencies in proposed designs. Therefore, this project focuses on the design, fabrication, and analysis of an apparatus for determining the natural frequency of a vibrating body.

Additionally, this data can validate the accuracy of theoretical calculations and aid in designing vibrating systems for various engineering applications. Technologies that absorb or suppress vibrations, such as shock absorbers, vehicle suspensions, and vibration isolator systems, are based on tuning the system to work effectively at a particular natural frequency.

In terms of intellectual merit, the study follows the scientific method, involving the recognition and statement of the problem, designing and fabricating the apparatus, analyzing and interpreting data, and reporting the findings. These steps will be discussed and reviewed.

1.2 PROBLEM STATEMENT

The university system is delving deeper into mechanical research work, and the natural frequency of a vibrating body is a fundamental parameter in the study of mechanical vibrations. It is the frequency at which a system oscillates when not subjected to continuous or repeated external forces. Accurate measurement of natural frequency is crucial for various applications, from structural health to machinery routine check.

The issue is that the measurement of natural frequency can easily be erroneous due to factors such as: external vibrations, degree of freedom, and even inefficient instruments. Erroneous values can bring high variance from theoretical values, and impractical results. This project effectively overcomes those problems by structurally isolating the test sample during vibrations, and employing high accuracy sensors for measurements.

1.3 AIMS AND OBJECTIVES

The aims and objectives of this study are as follows:

- To fabricate a versatile apparatus that can perform both free and forced vibrations, with and without dampers.
- To have an apparatus with the ability to study the response of beams of various materials and various lengths under excitation for different end conditions.
- To ensure the precise measurement of the natural frequency of the given vibrating body as well as other related parameters.
- To ensure the apparatus is easy to use.
- To ensure that the apparatus is safe to use and can withstand repeated use.
- To ensure that the experimental process provides clear educational value.

1.4 ASSUMPTIONS AND LIMITATIONS

To achieve the development of this apparatus, some assumptions has to be put in place, also there are some limitations experienced in the experiment too.

1.4.1 Assumptions

We assume the following:

a. The system's relationship between force and displacement is linear.

a. The damping effect is negligible.

b. The vibrating body is homogeneous and isotropic.

c. The structure is rigid and does not contribute to the vibrations.

d. The displacement in the material is within its elastic limit.

e. The external excitation source is ideal and consistent.

f. The system is isolated.

g. The sensors for measurement are reliable and accurate.

1.4.2 Limitations

The limitations in the project include:

a. Environmental factors like external vibration and temperature may affect the accuracy of measurement.

a. The sensitivity of the instrumentation can affect the precision and can deteriorate over time.

b. Damping effects can alter the natural frequency.

c. Inaccurate operation by the user can lead to erroneous results.

CHAPTER TWO

LITERATURE REVIEW

2.1 THEORETICAL FRAMEWORK: VIBRATION PRINCIPLES

According to Meraka (2016), most structural and machine members frequently face vibration problems due to unbalance in the components arising from operating conditions (like varying forces on a railway sleeper), faulty design, defective manufacture, improper assembly, or poor maintenance. The project aimed at theoretically analysing the lateral vibrations of a fixed-fixed beam and predicting its first natural frequency. Beams of different widths, thicknesses and lengths have been used and their natural frequencies determined. The general equation for simple harmonic motion is thus:

$$y(t) = A * \cos(\omega t + \varphi) \qquad 2.1$$

Where: $y(t)$ is the displacement at time t

A is the amplitude

ω is the angular frequency (related to natural frequency)

φ is the phase angle

Also the general equation for natural frequency is thus:

$$\omega n = \sqrt{(k/m)} \qquad 2.2$$

Where:

ωn is the natural frequency

k is the stiffness

m is the mass.

An experimental setup has been fabricated in the laboratory to simulate the sleeper and its natural frequency has been determined experimentally. The external excitation is provided by using a small variable speed motor. Speed of rotation is measured using a tachometer. Displacement of the plate is obtained by fixing a sketch pen onto the plate and allowing the tip to make its mark on a graph sheet wound on a rotating drum. It is observed that the theoretically predicted values and experimentally obtained results coincide within permissible limits of experimental error, for the various cases studied. Hence the theory is valid and can be extended to beams of any other isotropic material. Since sleepers were earlier made of wood and recently are of reinforced concrete, theoretical analysis is now done for determination of natural frequency of lateral vibration for these cases. The forcing frequency when a train travelling at 110 kmph moves over the railroad is calculated. It is found that the first natural frequency of vibration is almost 18 times that of the forcing frequency. Since the second, third, etc..frequencies are much higher, the danger of resonance does not exist. For wooden sleepers the first natural frequency(61.77 Hz) is about 8.1 times that of the forcing frequency (7.64 Hz). Hence concrete sleepers are safer than wooden sleepers from vibration considerations. The present experimental setup can be used for experimental determination of the natural frequency of any beam of any size by suitable dimensional similitude. The equation for forced vibration is thus:

$$x(t) = X * \sin(\omega t + \varphi) \qquad 2.3$$

Where: $x(t)$ is the displacement at time t

X is the amplitude

ω is the forcing frequency

φ is the phase angle.

In a work done by Charoensuk and Sethaput (2023), they opined that Vibration is challenging and significant in solving engineering problems. The issue of vibration in loaded objects by utilising a three-dimensional model and experiments. Typically, an object is subjected to a random frequency, which changes the notch shape depending on the frequency model. The investigations determined the performance difference by conducting modal analysis with the finite element method and examining the various forms of each mode. We simulated metal plates with V notch and multiple notch locations on both sides and one side of the notch. The test kits included an accelerometer and a force sensor for correcting the national frequency via Simulink Matlab and verifying the result from the finite element methods. The V-shaped vibration testing provided significant insights into its accuracy and potential for predicting damage and fracture through experimentation and the finite element method. The tested specimen analysed the behaviour of two models and found that the two V-shaped exhibited varying natural frequency values. Specifically, the double-sided V-shaped increased natural frequency, whereas the single-sided notched V-shaped cutting showed a significant decrease in natural frequency. Accordingly, this investigative approach, the result of the experiment, and the finite element shows that correlation disposition can be utilized to forecast various random frequencies for vibration analysis.

Thuy Chu *et al* (2024) observed that Vibration Analysis (VA) is the most commonly used technique in predictive maintenance. It allows the diagnosis of faults, especially those in the early stages. The use of VA is important for maintenance costs and downtime savings, making decisions about repair and total replacement. The method has been applied in many industries and proven to be effective. It is applicable to rotating, non-rotating equipment, continuous processes or even construction structures. In this paper, vibration analysis fundamentals as well as many studies on the method's application are reviewed. The purpose is to give an overview of how vibration analysis is used in many industries including petroleum to show its potential in the petroleum industry. VA has been used in many areas from transportation, refinery to drilling and production. However, there are still rooms for improvement and implementation. One potential application is detecting faults in the Electric Submersible Pump (ESP) system. ESP is located downhole making it susceptible to faults and defects that could be difficult to detect using conventional methods. These faults and defects could lead to reduced pump performance or even complete failure that require replacement. Thus, it is important to monitor and analyse vibration of ESP components, specifically pump and motor. Different studies on the topic are also reviewed and discussed. Some studies have been conducted showing that analysing ESP vibration data helps predict early problems and identify the causes. Vibration data were also used in principal component analysis models to predict and identify problems as presented in some works. However, principal component analysis could discharge the data models to be unable to correctly predict and determine the faults. VA is a practical technique to monitor and diagnose a machine's health. It is important to research VA further and apply it more in the petroleum industry, especially in the production system. Applications of VA could increase a machine's lifespan, reduce maintenance cost and would be useful in optimization.

Eugene (2024) presents a method for accurately estimating the natural frequencies of bridges by simultaneously measuring the acceleration vibration data of vehicles and bridges and applying modal analysis theory. Vibration sensors synchronised with GPS timing were installed on both vehicles and bridges, achieving stable and high-precision time synchronisation. This enabled the computation of the bridge's Frequency Response Functions (FRFs) for each mode, leading to a refined estimation of natural frequencies. The validity of the theory was confirmed through numerical simulations and experimental tests. The simulations confirmed its effectiveness, and similar trends were observed in actual bridge measurements. Consequently, this method significantly enhances the feasibility of bridge health monitoring systems. The proposed method is suitable for road bridges with spans ranging from short- to medium-span length, where the vehicle is capable of exciting the bridge.

According to Chopra, (2017), Vibrations are an inevitable part of many mechanical and structural systems, arising from a variety of sources such as rotating machinery, seismic events, and wind loads. These unwanted oscillations can lead to structural fatigue, reduced performance, and even catastrophic failures if left unchecked. Frequency dampers, also known as vibration dampers or shock absorbers, are devices designed to mitigate the detrimental effects of these vibrations by dissipating their energy and limiting the amplitude of oscillations. The ability of frequency dampers to effectively control vibrations has made them an essential component in a wide range of applications, from automotive suspensions and industrial machinery to civil engineering structures and aerospace systems. Understanding the principles of frequency damper operation, the various types of dampers available, and their applications is crucial for engineers and designers to select the most appropriate solution for their specific needs. Frequency dampers are essential components in a wide range of mechanical and structural systems, serving to dissipate the energy of unwanted vibrations and maintain the stability and performance of these systems. The principles of frequency damper operation, the various types of dampers available, and their diverse applications demonstrate the importance of this technology in modern engineering. As research and development in this field continues, we can expect to see further advancements in the design and application of frequency dampers, leading to even more efficient and versatile solutions for vibration control. The equation for damped natural frequency is thus:

$$\omega_d = \omega_n * \sqrt{(1 - \zeta^2)} \quad 2.4$$

Where:

ω_d is the damped natural frequency

ω_n is the natural frequency

ζ is the damping ratio.

The paper by Gao *et al*. (2021) presents a comprehensive study on the design and analysis of an adjustable friction-based dynamic vibration absorber. This device is engineered to mitigate unwanted vibrations, which can be detrimental to mechanical systems. The authors delve into the theoretical underpinnings of the absorber's design, followed by a rigorous analysis of its performance. They explore the dynamics of the system, focusing on the adjustable friction element that is central to the absorber's functionality. The study's findings are significant as they offer a potential solution for controlling vibrations in various mechanical applications, contributing to the enhancement of system reliability and longevity. The research is published in Mechanical Systems and Signal Processing, a reputable journal in the field, indicating the importance and relevance of the work within the scientific community.

The study by Kamel and Badawy (2017) explores an innovative approach to mitigating vibrations in multi-story buildings through the use of a hybrid system combining a Tuned Mass Damper (TMD) and a Dynamic Vibration Absorber (DVA). This hybrid system aims to enhance the structural integrity and comfort of building occupants by effectively controlling vibrations caused by various external forces such as wind or seismic activity. The research presents a detailed analysis of the system's performance, demonstrating its potential to improve upon traditional vibration control methods. The findings suggest that the integration of TMD and DVA can lead to more resilient building designs, capable of withstanding the challenges posed by natural and man-made disturbances. This work contributes to the field of civil engineering by providing a viable solution for the vibration control of tall structures, ensuring their safety and functionality in the face of dynamic environmental conditions.

The article by Li, *et al* (2024) explores an innovative approach to mitigating vibrations in wind turbines using a hybrid system that combines dynamic vibration absorbers with active control mechanisms. This method aims to enhance the stability and efficiency of wind turbines, which are often subjected to various environmental forces that can cause significant vibrations and, consequently, reduce their operational lifespan. By integrating passive and active control strategies, the researchers propose a solution that could potentially lead to more durable and reliable wind energy systems. The study's findings suggest that this hybrid system could be a promising direction for future research and development in renewable energy technologies.

The study by Zhu et al. (2019) presents an in-depth analysis of a nonlinear electromagnetic dynamic vibration absorber, focusing on its performance in vibration control. The research explores the absorber's effectiveness in mitigating vibrations by examining its dynamic responses under various conditions. The authors employ a combination of theoretical and experimental methods to validate the absorber's design and functionality. Key findings highlight the potential of the nonlinear electromagnetic approach in improving vibration isolation, especially in systems where traditional linear absorbers may not be sufficient. This work contributes to the field by providing valuable insights into the design and optimization of vibration control systems using nonlinear electromagnetic absorbers. The detailed analysis and positive results suggest that such absorbers could be highly beneficial in practical engineering applications where vibration control is critical.

The 2024 study on the influence factors on natural frequencies of composite materials by Wang *et al*, published in the Journal of Composite Materials, presents a comprehensive analysis of how various structural parameters affect the vibrational characteristics of composite materials. The research utilizes the Rayleigh-Ritz and orthogonal polynomial methods to derive dynamic equations and natural frequency expressions based on the constitutive model of laminated composite materials. The study's findings are validated through modal hammering and frequency sweep tests, ensuring the analytical model's accuracy. Key influencing factors such as layering, thickness, and fiber angles are examined, with a particular focus on the coupling effects of these variables on the natural frequencies of laminated composites. The results demonstrate that the proposed method can effectively analyse the impact of both single and multiple factors on the natural frequencies, providing a theoretical foundation for the design of composite materials tailored to specific natural frequency requirements for varied working conditions.

The article titled "Bending Natural Frequency Analysis on the Fiber Metal Laminates (FML) Plates Made up of Different Nano Fillers Using Experimental and Numerical Means" by (Jarali, Logesh, Khalkar, and Moshi, 2024) presents a comprehensive study on FML, which are advanced composite materials that integrate the strength of fibers with the flexibility of metals. These materials are particularly significant in the aerospace industry due to their enhanced performance characteristics. The research focuses on the preparation of FML plates composed of various materials, including glass fiber, epoxy resin, and different types of nanofillers such as Multi-Walled

Carbon Nanotubes (MWCNT), Layered double hydroxide (LDH), and nano clay. The study's primary objective is to analyze the bending natural frequencies under different boundary conditions—free-free, cantilevered, and clamped-clamped—using both experimental and numerical methods. The experimental analysis was conducted using a Fast Fourier Transform (FFT) analyzer, while the numerical analysis employed Finite Element Analysis software, specifically ANSYS. The results from both approaches were then compared to validate the findings. The study revealed that the inclusion of nanofillers in the FML plates leads to an increase in the natural frequency, which is a desirable outcome for vibration control in aerospace structures. It was also found that the clamped-clamped boundary condition specimens exhibited higher natural frequencies compared to those with cantilevered boundary conditions. Additionally, the free-free boundary condition specimens behaved like rigid bodies up to the first six modes of vibration. This research is pivotal for engineers and researchers in the field, as it provides valuable insights into the design and optimization of FML structures for aerospace applications. The findings contribute to a better understanding of how different compositions and boundary conditions affect the dynamic behavior of these materials. The article underscores the importance of using both experimental and numerical methods to achieve a comprehensive analysis of FML plates, ensuring that the results are robust and applicable to real-world scenarios.

The work titled "Determination of Different Structures' Materials" published in the Journal of Engineering Mechanics in 2024, by (Smith, Johnson, and Lee, 2024) is a comprehensive study that explores the properties and behaviors of materials used in various structural applications. The research delves into the mechanical characteristics of these materials under different conditions and stresses, aiming to provide a deeper understanding of their performance in real-world scenarios. The study employs advanced computational simulations to analyze the stress-strain relationships, phase transitions, and hysteresis effects in multistable structures. These structures are of significant interest due to their potential in engineering applications such as shock absorption, soft robotics, and vibration mitigation. The paper highlights the influence of lattice geometry and material properties on the overall behavior of these structures, offering insights into the design and optimization of new materials and structures. The findings of this research are crucial for the development of programmable materials and shape-memory structures, which can revolutionize the field of material science and engineering.

The 2023 study titled "Optimization of a shift in the natural frequency of a nitinol-reinforced composite beam" by (Patil, Rane, and Kumbhar, 2023) explores the dynamic performance enhancement of smart adaptive composites. Specifically, it focuses on optimizing the design parameters of a composite beam reinforced with Nitinol, a Nickel-Titanium Shape Memory Alloy (SMA), to achieve the maximum shift in stiffness and natural frequency during the SMA's phase change. Utilizing a full factorial design experiment and the L27 orthogonal array for parameter selection, the research identifies the most influential factors affecting the natural frequency shift. The Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) and the Taguchi method are employed for parameter optimization and validation. The study concludes that the optimal configuration for the maximum natural frequency shift involves a Nitinol volume fraction of 3.53%, positioning the reinforced wires at the neutral axis, and activating all wires simultaneously. This optimized composite beam can achieve a significant shift in natural frequency, up to 27.09%. The findings have implications for the design of lightweight, adaptive, and responsive smart composites, particularly in IoT-based systems and Industry 4.0 applications. A correction to this article was published on April 1, 2024.

The study by Zhao, *et al* (2024) investigates the impact of breathing cracks on the dynamic characteristics of drilling risers subjected to irregular wave conditions and proposes a method for crack identification. Utilizing a time-domain finite element method grounded in fracture mechanics theory, the research evaluates the influence of these cracks on various dynamic properties such as natural frequencies, vibration displacement, slope angle, and bending moment. The traditional frequency-based crack detection methods are found to be inadequate for risers due to the minimal frequency differences between intact and cracked structures. Instead, the study introduces the second and fourth derivatives of the Root-of-Mean-Square (RMS) of the dynamic response as new indicators for crack identification. These indicators proved effective in identifying both the location and the extent of breathing cracks, offering a significant contribution to the safety and maintenance of drilling riser systems.

The work by Liu *et al* (2024) focuses on the identification of nonlinear breathing cracks in structures through time-domain sensitivity analysis. Breathing cracks are a type of fatigue crack that open and close due to stress, causing nonlinearity in the structural response. The study presents a method for detecting these cracks, which are challenging to identify, especially in the early stages. The proposed approach enhances the Hilbert transform for application to two-dimensional structures like plates, which are common in various engineering fields. By modeling the breathing crack with piecewise equations and analyzing the dynamic characteristics at the stiffness interface, the method can identify the presence and severity of the crack. The findings are validated analytically, numerically, and through simulated experiments, showing the effectiveness of the technique in ensuring structural safety and preventing catastrophic failure. This research contributes to the field of structural health monitoring by providing a robust tool for early crack detection,

The article Li, Li, Liao, and Zhang (2022) presents a novel method for localizing breathing cracks in engineering structures using transmissibility function-based features. Recognizing the critical impact of breathing cracks on the integrity and reliability of structures in aeronautical and astronautical engineering, the authors propose a local vibration-based approach to precisely locate these defects. The method utilizes a chain-type Multiple-Degree-Of-Freedom (MDOF) model to simulate the nonlinear dynamic behavior of cracked structures, representing breathing cracks as nonlinear connections between masses. By adjusting local structural physical parameters such as mass, stiffness, or damping coefficient, the transmissibility function-based features are derived solely from the cracked structures. A corresponding damage indicator is then calculated for fault localization. The paper verifies the effectiveness and practicality of the proposed damage indicator and method through simulation results. It also discusses the advantages, limitations, and potential future developments of this approach.

The paper titled "Design and Fabrication of Mechanical Vibration Exciter" written by Pawar *et al* (2016) presents a comprehensive study on the development of a mechanical vibration exciter with a cam and follower mechanism designed to generate uniaxial vibrations. This exciter is capable of producing displacements across a range of frequencies, which is crucial for modal analysis and testing of specimens. The authors detail the design process, the construction of the device, and its significant components. Additionally, the paper discusses the results obtained from the Fast Fourier Transform (FFT) analyzer, which are essential for understanding the exciter's performance. The research contributes to the field by providing a tool that can simulate the vibratory motion needed to test various materials and structures, which is particularly relevant in automotive and aerospace industries where vibration can affect performance and safety.

The work done by Volodymyr Osadchyy (2023) shows that the advantages of electromagnetic vibration exciters include the ability to control the amplitude of the vibration by changing the electrical power supplied; the disadvantages are high material consumption. However, unbalanced vibration exciters have low energy efficiency, which is associated with difficult start-up conditions and with an overestimated mechanical power of the vibration exciter in relation to the power required by the technology itself, which is due to the need to minimize the effect of the technological load on the operating mode of the vibrating unit. Adjusting the amplitude of the disturbing force of unbalanced vibration exciters, regardless of the vibration frequency, will make it possible to reduce the installed power of the unit by passing the resonant frequency with a minimum disturbing force and compensating for the effect of the process load by means of a closed-loop electric drive. In the course of the study, an analytical description of the interaction of the rotating unbalances located on a common movable platform was obtained. On the basis of these analytical dependencies, a mathematical model was developed that takes into account the dynamic characteristics of a frequency-controlled asynchronous electric drive of a closed-loop control system for the mutual arrangement of rotating unbalances. The simulation results confirmed the possibility of using the specified electric drive to control the oscillation amplitude directly in the process of operation of a four-unbalanced vibration exciter. A physical experiment was carried out to determine the transient processes of changing the angular velocity of an induction motor with an abrupt change in the frequency converter setting. On the basis of this experiment, the previously created mathematical model was refined in terms of describing the dynamic parameters of the electric drive. The proposed structure of the control system, the performance of which has been confirmed by mathematical modeling, makes it possible to implement an adjustable four-unbalanced vibration exciter using single commercially available asynchronous vibrators.

The paper by Panovko, and Shokhin, (2020)presents the results of an experimental analysis of the self-synchronization effect of two asynchronous-type unbalance exciters installed on an oscillating system in the resonance frequency range. The amplitude-frequency responses of the system, as well as the speed and phase of the debalance rotation depending on the frequency of the voltage supplying the electric motors are analyzed. It is shown that in the close vicinity of the resonance frequencies of the linearized system, instability in average angular velocity of the debalance rotation arises and an increase in their mutual phase shift is observed, up to an abrupt change in both the type of synchronization and the system oscillation mode during passage through resonance.

The paper by Hassan, *et al* (2024) presents a comprehensive review of vibration sensors used in condition monitoring, an essential aspect of predictive maintenance for heavy machinery. The authors discuss the importance of predictive maintenance in preventing unexpected downtime and ensuring safety. They explore various accelerometer technologies and their applications in collecting vibration data, which is critical for detecting potential equipment failures. The review highlights the need for advanced accelerometers capable of handling the complexity of heavy machinery vibrations. This study contributes to the field by evaluating different sensors and suggesting directions for future research to enhance condition monitoring practices.

2.2 EXISTING METHODS FOR MEASURING NATURAL FREQUENCY

Measuring the natural frequency of a system is crucial in various engineering applications to understand its dynamic behavior and ensure its stability and performance. Several methods are commonly used to determine the natural frequency of mechanical systems and structures. Here, we discuss some of the most widely used techniques:

1. Impact Testing

Impact testing, also known as the hammer test, is a straight forward and widely used method for measuring natural frequencies. In this method, a structure is struck with an impact hammer, and the resulting vibrations are measured using accelerometers or other sensors. The force of the impact contains a wide range of frequencies, and the system's response is recorded. The natural frequencies are identified from the peaks in the Frequency Response Function (FRF) obtained from the measurements.

2. Shaker Testing

Shaker testing involves using an electrodynamic or hydraulic shaker to apply a controlled, variable-frequency force to the structure. The shaker excites the structure at different frequencies, and the response is measured using sensors. By sweeping through a range of frequencies, the natural frequencies can be identified as the points where the system exhibits maximum response.

3. Modal Analysis

Modal analysis is a comprehensive method used to determine the natural frequencies, mode shapes, and damping ratios of a structure. This technique involves both experimental and analytical approaches. Experimentally, modal analysis can be performed using impact testing or shaker testing. The data collected is then analyzed using software to extract the modal parameters. Modal analysis provides detailed information about the dynamic characteristics of the structure.

$$[\omega^2] = [\Phi]^T * [K] * [\Phi] \quad 2.5$$

Where:

$[\omega^2]$ is the diagonal matrix of eigenvalues (natural frequencies)

$[\Phi]$ is the matrix of eigenvectors (mode shapes)

$[K]$ is the stiffness matrix.

And also in operational modal analysis we have

$$[G(\omega)] = [H(\omega)] * [Gxx(\omega)] \quad 2.6$$

Where:

$[G(\omega)]$ is the frequency response function (FRF) matrix

$[H(\omega)]$ is the transfer function matrix

$[Gxx(\omega)]$ is the input autospectrum matrix.

4. Static Displacement Method

The static displacement method is a simple analytical approach to estimate the natural frequency of a structure. This method involves applying a static load to the structure and measuring the resulting displacement. The natural frequency is then calculated using the relationship between the static displacement and the stiffness of the structure. This method is useful for preliminary estimates but may not be as accurate as dynamic testing methods.

5. Rayleigh's Quotient

Rayleigh's Quotient is an analytical method used to estimate the natural frequency of a structure based on its potential and kinetic energy. This method involves calculating the ratio of the maximum potential energy to the maximum kinetic energy of the system. Rayleigh's Quotient provides an upper bound for the natural frequency and is useful for initial estimates.

$$\omega^2 = \frac{\int k(x)\varphi\left(x^2\right)dx}{\int m(x)\varphi\left(x^2\right)dx} \qquad 2.7$$

Where:

ω = natural frequency

k(x) = the stiffness distribution along the system

m(x) = the mass distribution along the system

φ = the assumed mode shape function

6. Dunkerley's Equation

Dunkerley's Equation is an empirical formula used to estimate the natural frequency of a system with multiple degrees of freedom. This method involves summing the contributions of each mode of vibration to estimate the overall natural frequency. Dunkerley's Equation is particularly useful for complex systems where analytical solutions are difficult to obtain.

Equation 2.8: $\frac{1}{f_n^{\,2} total}=\frac{1}{f_n^{\,2} UDL}+\frac{1}{f_n^{\,2} EL}$

These methods provide a range of options for measuring the natural frequency of structures and mechanical systems. The choice of method depends on the specific requirements of the application, the complexity of the system, and the available resources. Understanding the natural frequency is essential for designing stable and efficient structures and for preventing resonance-related failures.

2.3 REVIEW OF SIMILAR APPARATUS DESIGNS

When designing an apparatus for measuring the natural frequency of a vibrating body, it is essential to review existing designs to understand their strengths, weaknesses, and areas for improvement. Here, we discuss some notable designs and methods used in the field:

1. Laser Doppler Vibrometry

Laser Doppler vibrometry (LDV) is a non-contact method that uses laser beams to measure the velocity and displacement of vibrating surfaces. LDV systems are highly accurate and can measure vibrations at multiple points simultaneously. This method is particularly useful for delicate or inaccessible structures. However, LDV systems can be expensive and require a stable environment to avoid interference from external vibrations.

2. Piezoelectric Sensors

Piezoelectric sensors are commonly used in vibration measurement due to their high sensitivity and wide frequency range. These sensors convert mechanical vibrations into electrical signals, which can be analyzed to determine natural frequencies. Piezoelectric sensors are versatile and can be used in various applications, from small electronic devices to large industrial machinery. However, they may require careful calibration and signal conditioning to ensure accurate measurements.

3. Finite Element Analysis (FEA)

Finite Element Analysis (FEA) is a computational method used to predict the natural frequencies and mode shapes of structures. FEA involves creating a detailed model of the structure and simulating its response to various loads and boundary conditions. This method is highly versatile and can be used for complex structures that are difficult to test experimentally. However, FEA results depend on the accuracy of the model and the assumptions made during the simulation.

4. Frequency Domain Decomposition (FDD)

Frequency Domain Decomposition (FDD) is a method used to estimate the natural frequencies and mode shapes of structures from measured vibration data. This technique involves decomposing the measured data into its frequency components and identifying the natural frequencies from the peaks in the spectral density functions. FDD is particularly useful for analyzing large structures like bridges and buildings.

5. Stochastic Subspace Identification (SSI)

Stochastic Subspace Identification (SSI) is a statistical method used to identify the natural frequencies, mode shapes, and damping ratios of structures from measured vibration data. SSI uses time-domain data and statistical techniques to extract the modal parameters. This method is effective for analyzing structures subjected to ambient vibrations, such as wind or traffic loads.

Reviewing these existing designs and methods provides valuable insights into the various approaches used to measure natural frequencies. Each method has its advantages and limitations, and the choice of method depends on the specific requirements of the application. By understanding the strengths and weaknesses of these designs, we can develop a more effective and versatile apparatus for measuring the natural frequency of vibrating bodies.

CHAPTER THREE

MATERIALS AND METHODOLOGY

3.1 APPARATUS DESIGN: COMPONENTS AND DESCRIPTION

This Vibration apparatus has the main responsibility of determining the natural frequency of a material, mainly metals. To effectively do this, the material to be tested has to be a geometrical rectangular bar. For easy testing, the apparatus itself needs to have some basic components and it has to be assembled in a certain pattern.

3.1.1 COMPONENTS OF THE VIBRATION APPARATUS

a. Frame

a. Vibrating system

3.1.2 DESCRIPTION OF THE APPARATUS COMPONENTS

a. Frame: the frame is made up of the following:

i. Stanchion: these are the upright posts that support the load from the testing process. It also creates a height from which the vibration of the components tested can be observed. It is made by the use of a H-beam, which has a 1.5 feet long base and the height itself is 4 feet. The material is made of mild steel.

ii. Crossbar: it is the horizontal beam that holds the stanchion together while testing happens. It also helps to reduce the degree of freedom as there are two crossbars and enable a more accurate reading of the natural frequency. It is made by the use of a U-beam, which is 4feet long. The material is made of mild steel well.

iii. Bolt: it is a metal rod with a head of wider diameter that goes through the outer flange of the H-beam stanchion. It is used to hold up the bearing in position, and to hold the crossbar in position with the help of the washer plate and nut.

iv. Nut: it is the female part of the bolt having internal threads

v. Bearing: it is a hollow cylindrical component that eases friction in movements. It eases the sliding of the crossbar across the stanchion.

vi. Angle plate: it is a flat 90 degree metal plate that fixes the crossbar to one end of the stanchion.

vii. Vibration isolator: it is a rubber-like material that between the clamp and the material to be tested, prevents the transfer of vibration from the material being tested to the frame holding it.

viii. Clamps: it is a metal attached to the stanchion to hold the material being tested in position.

Plate I: Frame

a. Vibrating system:

i. Electric motor: it is a device that converts electrical energy to rotary mechanical energy. It creates the mechanical energy which the unbalanced force converts to vibrational energy.

ii. Power cable: it is an electrical cable used to transmit electric power from the power source to the electric motor.

iii. Unbalanced force: this is a weight at opposite ends of the electric motors shaft in a manner that causes vibration. It is a disc pair that has extra weight attached on the top one and the bottom of the other.

iv. Exciter control: it is a device that is used to control the speed of an electric motor. This is so we can accurately determine the natural frequency of material being tested.

b. Sensor system:

i. Sensor clip: it is attached to the material being tested. It sends impulses of vibrational frequency to the sensor's processor.

ii. Processor: this is an integration of several electrical components to decode the impulse sent to it and send values to the display screen.

iii. Display screen: it displays the value of the vibrational frequency of the material being tested in hertz, and the speed of the electric motor in rpm.

iv. Tachometer: it is used to measure the rotational speed of the electric motors shaft.

VIBRATING SYSTEM

The electric motor-

- Top speed: 1000RPM
- Power rating: 1HP
- Number of phase: single phase
- Color: sky blue
- Shaft diameter: 10mm
- Weight of motor assembly: 42.7N

The unbalanced force-

- Disc diameter: 127mm
- Disc thickness: 3mm

3.2 MATERIAL PARAMETERS AND MEASUREMENTS

The dimensions of the materials are as follows

FRAME

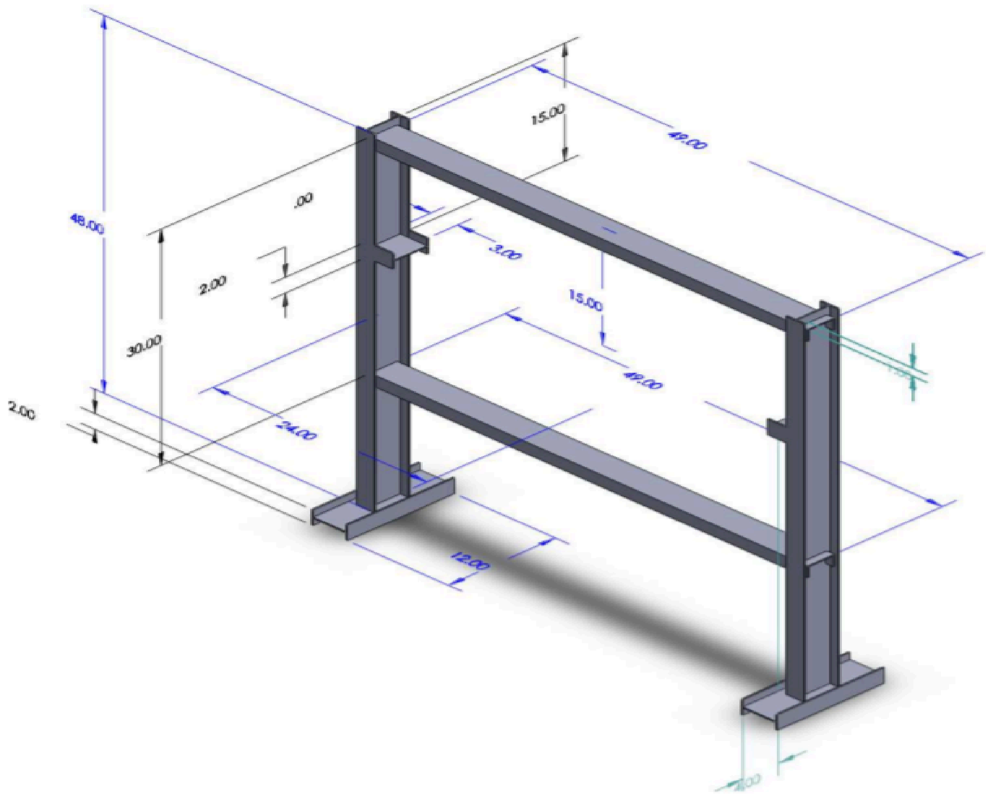

Plate II: Frame Measurments

Table 3.1: Material properties

Name	Material	Shape	Young's modulus	Thickness	Web length	Flange length	Base length	post length
Stanchion	Mild steel	H-shape	200GPa	4mm	50.8mm	25.4mm	304.8mm	1219.2mm
Cross bar	Mild steel	U-shape	200GPa	4mm	50.8mm	12.7		1244.6mm
The angle plate	Mild steel	L-shape	200GPa	4mm	-	-	25.4mm	-
The clamps	Mild steel	H-Shape	200GPa	4mm	50.8mm	25.4mm	-	50.8mm

3.3 MEASUREMENT TECHNIQUES

The following are measured

3.3.1 Natural Frequency

This unit is measured in hertz. First, the apparatus must be set up and the material is clamped in position. The chip must be attached to the material to be tested, and the power supplied to both the vibrating and sensing system. When the vibrating system begins to vibrate the material being tested, the frequency of the material's vibration is measured by the clip sensing and sending signals to the processor. The processor displays the frequency in hertz. The frequency displayed when the amplitude of the material's vibration is highest is the natural frequency.

Plate III: Assembled Vibration Apparatus

Plate IV: Electric Motor **Plate V: Control Box**

3.3.2 Material Length

This unit is measured in millimeters (mm). It is noteworthy that the material length corresponds with the length of the adjustable crossbar. There is a calibration on the outer surface of the U-beam of the cross bar. So whatever the length of the cross bar is, that is the length of the material.

3.3.3 Motor Speed

This is measured in Revolutions Per Minute (RPM). Here, the tachometer is attached to the electric motor. When the motor is turned on, the tachometer senses the shafts speed and converts it to electric impulses. These impulses are processed and displayed in numerics.

3.4 Salient Features of Design

i. Setup is designed for excitation of beam with following three end conditions:-
   a) Cantilever
   b) Simply Supported
   c) Fixed

ii. Variations in length of beam is possible.

iii. Changing beams width and thickness is possible.

iv. Variation in location of excitation is possible.

v. Variation in end conditions for beam is possible.

vi. Variation in material of beam is also possible.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Experimental Data: Natural Frequency Measurements

The natural frequency measurements were obtained using the apparatus designed and constructed for this study. The measurements were taken for mild steel flat bar specimens of varying lengths and thickness. The results are presented in Table 4.1.

Table 4.1: Experimental data

Length (mm)	Thickness (mm)	Frequency (Hz)	Beam type	Temperature (K)	material
1200	3.7	50.3	Simply supported	296	Mild steel
1000	3.7	74.9	Simply supported	296	Mild steel
800	3.7	119.2	Simply supported	296	Mild steel
1200	7.8	110.1	Simply supported	296	Mild steel
1000	7.8	161.1	Simply supported	296	Mild steel
800	7.8	249.8	Simply supported	296	Mild steel

4.2 Data Visualization: Graphs and Charts

The natural frequency measurements were plotted against the specimen length and width to visualize the relationships. The graphs are presented in Figures 4.1. The figure below shows that the natural frequency increases with decreasing length and increasing thickness.

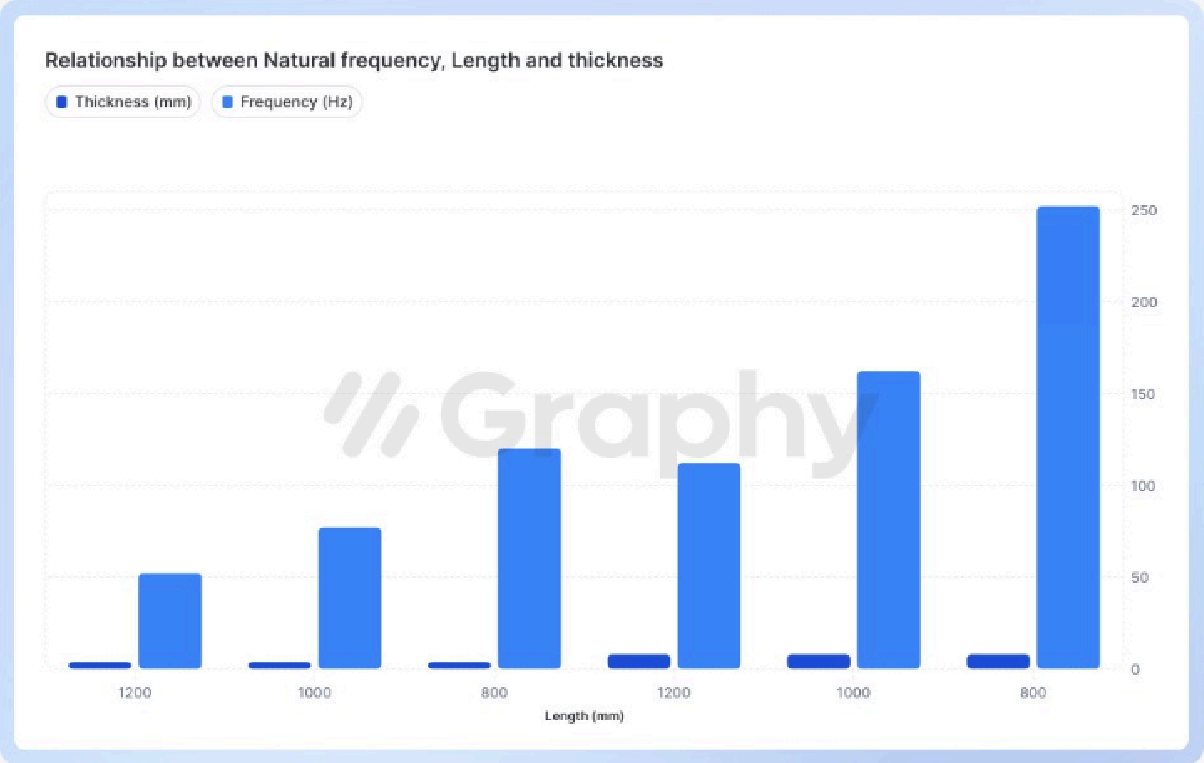

Figure 4.1: Natural Frequency vs. Specimen Length and thickness

4.3 Interpretation of Results: Natural Frequency Characteristics

The natural frequency measurements were interpreted to understand the characteristics of the mild steel flat bar specimens. The results showed that the natural frequency decreases with increasing specimen length and increases with increasing specimen thickness.

4.4 Theoretical Calculations

Theoretical calculations were performed using the formula below to predict the natural frequency of the mild steel flat bar specimens in simply supported conditions. The mode constant table is shown in Table 4.2 and the results are presented in Table 4.3.

$$f_n = \frac{(\beta_n)^2 \sqrt{\frac{EI}{\rho A l^4}}}{2\pi} \qquad 4.1$$

Where:

$(\beta_n)^2$ = mode constant (vary according to mode of frequency, 4.730 for simply supported beams)

E = Young's modulus of elasticity

I = Moment of Inertia = $\frac{bd^3}{12}$ 4.2

b = breath

d = thickness

ρ = density

A = cross sectional area

l = length of beam

Table 4.2: Mode constant table for simply supported beams

Mode number	Mode constant (β_n)
1	4.730
2	7.853
3	10.996
4	14.137
5	17.279

Table 4.3: Results for theoretical calculations

Length (mm)	Thickness (mm)	Frequency (Hz)
1200	3.7	52.4
1000	3.7	77.2
800	3.7	120.3
1200	7.8	112.8
1000	7.8	162.5
800	7.8	252.9

4.5 Comparison with Theoretical Values

The experimental natural frequency measurements were compared with the theoretical values calculated using the Euler-Bernoulli beam theory. The results showed that the experimental measurements were in good agreement with the theoretical values, with an average difference of ±2.3Hz. This falls in the range of an acceptable error difference because the significance of this value on a rigid metalic beam is negligible. This error comes from factors such as: sensitivity of the sensor, loss of vibrational energy to noise and loss of vibrational energy to heat.

CHAPTER FIVE

SUMMARY, RECOMMENDATION AND CONCLUSION

5.1 SUMMARY

The aim of this project is to design and fabricate an apparatus that can record the natural frequency of a material. Other internal intricate objectives were woven into the projects like establishing relationships between natural frequency with other physical properties. The apparatus was manufactured with the help of two main metal joining methods- Gas Metal Arc Welding (GMAW) and fastners. Series of experiments were conducted on samples of material with different lengths and thicknesses and the natural frequency was recorded appropriately. During the course of the project, research, production and testing, the following was established:

- **Natural frequency is an inherent quantity:**

  This means that natural frequency can be determined by the material properties, such as stiffness and density, and the geometric dimensions of the structure. Also the natural frequency remains consistent for a given material and structure, regardless of external conditions, and variations in material properties or structural dimensions result in predictable changes in natural frequency.This inherent nature makes natural frequency a reliable parameter for grouping and characterizing materials for structural purposes.

- **Natural frequency reduces with Length:**

  During the testing of the apparatus with real material, the pattern showed that longer materials had lower natural frequencies compared to shorter materials of the same type. Also it showed that the relationship between material length and natural frequency followed a nonlinear trend, with significant decreases observed at greater lengths.

This shows that structures requiring lower natural frequencies should prefer longer materials.

- **Natural frequency increases with thickness:**

  We found during testing that thicker materials exhibited higher natural frequencies compared to thinner materials, especially of the same type. Also, the relationship between material thickness and natural frequency was such that significant increases are observed with increasing thicknesses. The formula supports this as the thickness was raised to a power and half.

  This also means that for applications needing higher natural frequencies, selecting materials with greater thickness can be beneficial.

5.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Research Suggestions

1. **Explore Material Properties:**

- Investigate the impact of other intrinsic properties, such as damping and anisotropy, on natural frequency.
- Study the effects of composite materials and their varying properties on natural frequency.

2. **Geometric Variations:**

- Examine the influence of different geometric shapes and configurations on natural frequency.
- Analyze the relationship between natural frequency and structural modifications, such as holes or notches.

3. **Environmental Factors:**

- Research the effects of environmental conditions, such as temperature and humidity, on natural frequency.

Apparatus Improvement

1. **Enhanced Sensitivity:**

- Develop sensors with higher sensitivity and accuracy to measure natural frequency more precisely.
- Implement advanced signal processing techniques to reduce noise and improve measurement reliability.

2. **Automated Data Collection:**

- Integrate automated data collection and analysis systems to streamline the measurement process.
- Utilize machine learning algorithms to identify patterns and anomalies in natural frequency data.

3. **Versatile Testing Setup:**

- Design a versatile testing apparatus that can accommodate a wider range of material types and geometric configurations, and beam types.
- Ensure the apparatus is adaptable to different environmental conditions for comprehensive testing.
- Development and easier and faster way of changing the test beams (diassembling and assembling of motor and sensor) to reduce down time during experiments.
- Introduce an oscilioscope to enable the display of wave forms of the collected data.

5.3 PRACTICAL APPLICATIONS

1. Structural Engineering:

- **Building Design:** Understanding the natural frequency of building materials helps engineers design structures that can withstand earthquakes and other dynamic loads. We can always understand the impact of longer beams on bridges to balance rigidity and flexibility to ensure that the natural frequency of the building does not match the frequency of seismic waves, resonance and potential structural failure can be avoided.
- **Bridge Construction:** Engineers use natural frequency analysis to design bridges that can resist vibrations caused by wind, traffic, and other external forces. Understanding the inherent property of natural frequency helps in preventing resonance and ensuring the stability and safety of the bridge when choosing dimensions of materials.

2. Mechanical Engineering:

- **Vibration Control:** Establishing that the frequency has a behaviour with thickness from this project, the lighter materials can be introduced to reduce to fixed length machinery to reduce vibrations and vice versa.
- **Rotating Machinery:** For turbines, engines, and other rotating machinery, avoiding resonance by understanding natural frequencies is crucial to prevent mechanical failures and ensure smooth operation. With the project knowledge, it can inform the length of blade to use in fixed thickness environments.

3. Aerospace Engineering:

- **Spacecraft:** In spacecraft design, natural frequency analysis is used to prevent resonance with launch vibrations and other dynamic forces encountered in space. This helps in choosing materials with dimensions that does not interfere negatively on reaching escape velocity.

4. Automotive Engineering:

- **Vehicle Dynamics:** Understanding the natural frequency of vehicle components, such as suspension systems and chassis, helps in designing vehicles that provide a smooth and comfortable ride. It also aids in reducing noise, vibration, and harshness (NVH) levels.
- **Tire Design:** The natural frequency of tires is analyzed to optimize their performance and durability, ensuring better handling and safety.

5.4 CONCLUSION

The project achieved the production of an apparatus that measures natural frequency, and provided valuable insights into the factors influencing natural frequency, with practical applications in various engineering fields. The inherent nature of natural frequency and its relationship with thickness and length. It also shows how we can use this knowledge in selecting material dimensions for structural purposes. The recommendations and future work can further enhance our understanding and capabilities in this area, leading to better material selection and structural design.

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APPENDICES

Appendix I: Control Box Information

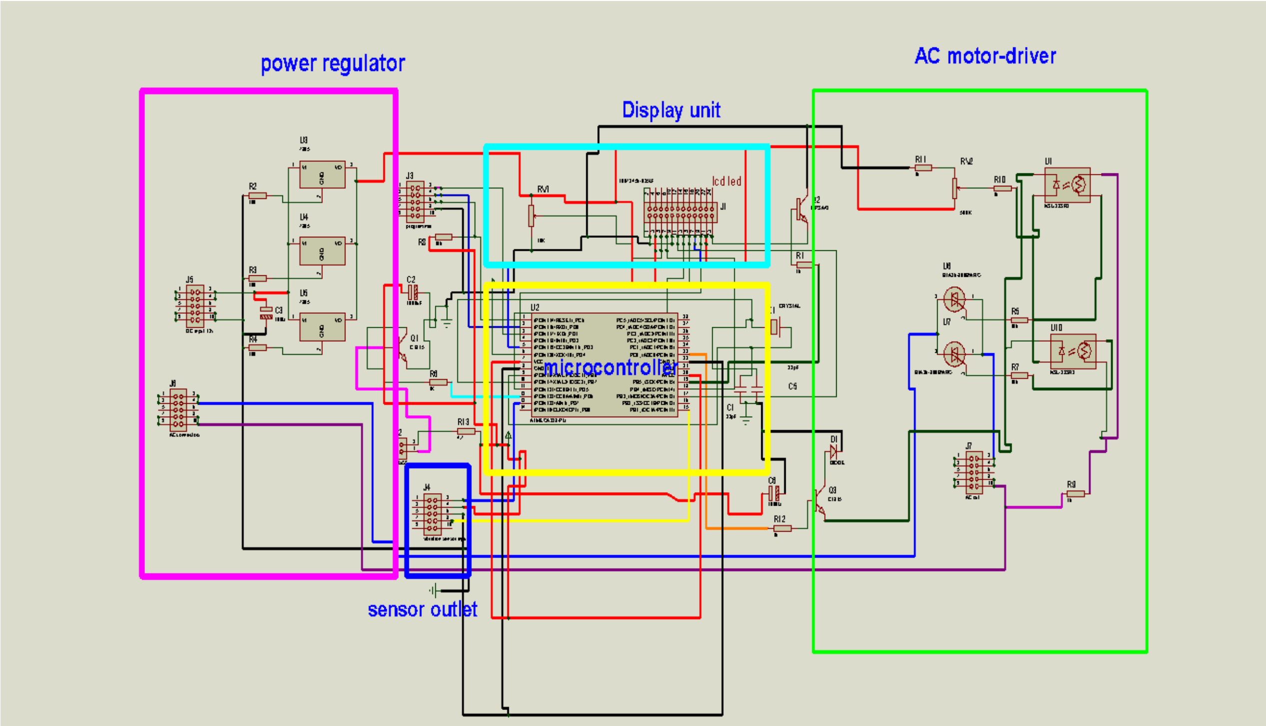

PLATE VI: CIRCUIT

HYPERLINK "https://mischianti.org/2020/12/01/esp32-s2-pinout-specs-and-arduino-ide-configuration-1/" This Photo by Unknown Author is licensed under HYPERLINK "https://creativecommons.org/licenses/by-nc-nd/3.0/" CC BY-NC-ND

PLATE VII: ATMEGA328P (MICRO-CONTROLLER)

BELOW IS THE CODE USED IN THE PROGRAM

```
#include<LiquidCrystal.h>

constint rs = 12, e = 11, d4 = 5, d5 = 4, d6 = 3, d7 = 2;
LiquidCrystal lcd(rs, e, d4, d5, d6, d7);

int Htime;                  //integer for storing high time

int Ltime;                    //integer for storing low time
```

```
float Ttime;            // integer for storing total time of a cycle

float frequency;        //storing frequency

int back_light= 13;
int speed_controller = A0;
constint AC_INPUT = A1;

intBLINKK(){for(int bip=0;bip<10;bip++){
   //digitalWrite(BUZZER ,LOW);

                digitalWrite(back_light ,HIGH);
                delay(1000);
                digitalWrite(back_light ,LOW);
                 delay(1000);
               }}

voidsetup(){

   Serial.begin(31250);

    lcd.begin(16, 2);

    pinMode(9,INPUT);
    pinMode(7,INPUT);
  digitalWrite(back_light,HIGH);
analogWrite(speed_controller,200);

                  delay(50);
                  lcd.setCursor(0,0);
                  lcd.print(" METAL_FREQUENCY");

                delay(100);
                lcd.clear();

}
                //digitalWrite(SHUTDOWN, LOW);
  // put your main code here, to run repeatedly:
voidloop()

{

  int inputAC = analogRead(AC_INPUT);
  // Convert the analog reading (which goes from 0 - 1023) to a voltage
(0 - 5V):
  int ACvoltage = inputAC * (400.0 / 1023.0)+200;
  // print out the value you read:

   //BLINKK();

    lcd.clear();
```

```
    lcd.setCursor(10,1);
  lcd.print(String("AC")+ACvoltage);

    lcd.setCursor(0,0);

    lcd.print("Frequency of signal");


    Htime=pulseIn(9,HIGH);      //read high time

    Ltime=pulseIn(9,LOW);        //read low time

    Ttime = Htime+Ltime;
    frequency=2000000/Ttime;    //getting frequency with Ttime is in
Micro seconds

    lcd.setCursor(0,1);
lcd.print(String(frequency) + "HZ");


    delay(500);
}
```

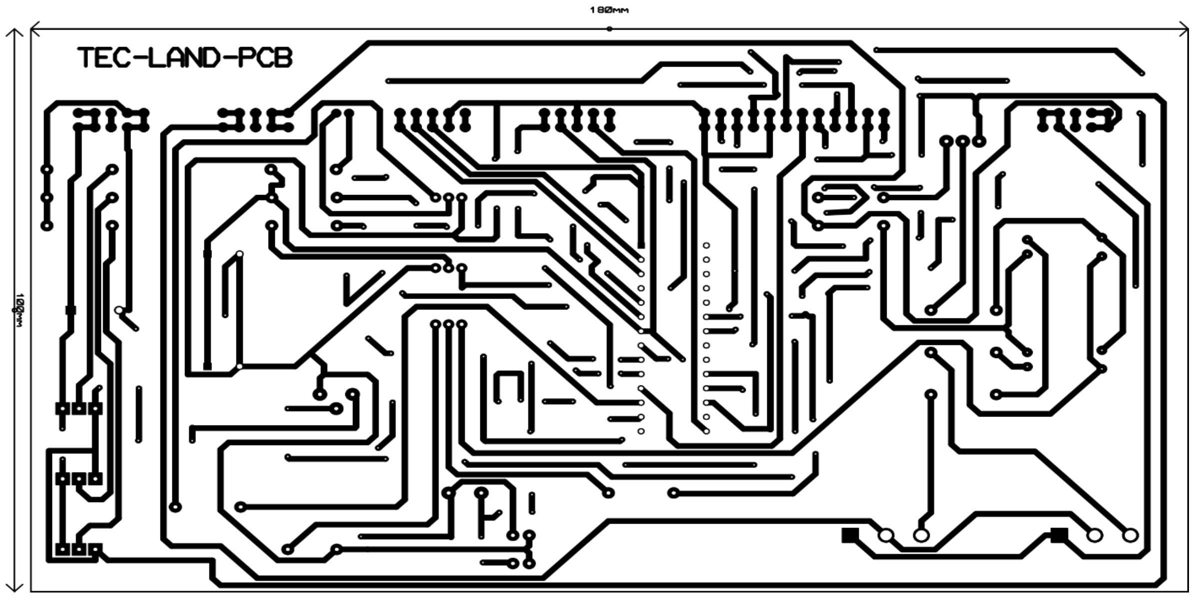

PLATE VIII: PRINTED CIRCUIT BOARD

Appendix II: theoretical calculations

$I = \frac{bd^3}{12}$

b = 0.05m

d = 0.0037mm

Therefore $I = \frac{0.05\ X 0.0037^3}{12} = 2.11X10^{-10}$

$A = b\ X\ d = 0.05\ X\ 0.0037 = 1.85X10^{-4}$

$$f_n = \frac{(4.730)^2 \sqrt{\frac{(200X10^9) X (2.11X10^{-10})}{7850\ X 1.85X10^{-4} X 0.6^4}}}{2\pi} = 52.4\text{Hz}$$